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# Resolving the impasse in American energy policy: The case for a transformational R&D strategy at the U.S. Department of Energy

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**Abstract**

From its inception in 1977, the U.S. Department of Energy (DOE) has been responsible for maintaining the nation's nuclear stockpile, leading the country in terms of basic research, setting national energy goals, and managing thousands of individual programs. Despite these gains, however, the DOE research and development (R&D) model does not appear to offer the nation an optimal strategy for assessing long-term energy challenges. American energy policy continues to face constraints related to three ''I's'': *inconsistency*, *incrementalism,* and *inadequacy.* An overly rigid management structure and loss of mission within the DOE continues to plague its programs and create *inconsistencies* in terms of a national energy policy. Various layers of stove-piping within and between the DOE and national laboratories continue to fracture collaboration between institutions and engender only slow, *incremental* progress on energy problems. And funding for energy research and development continues to remain *inadequate*, compromising the country's ability to address energy challenges. To address these concerns, an R&D organization dedicated to transformative, creative research is proposed.


*Keywords:* Energy policy; Innovation; Research and development; Transformative research; U.S. Department of Energy; ARPA-E

**Contents**



## 1. Introduction

Imagine walking into a building where a hybrid, multi-functional solar-lighting system utilizes direct sunlight to provide part of its illumination and automatically switches on and off as you traverse down the hallway. Conceptualize a refinery that incorporates algae and other unconventional feed-stocks in its manufacturing of biofuel. Envision stepping into a fully automated personal land transit system that takes you effortlessly across town. Are each of these ideas eccentric and unconventional, perhaps even slightly far-fetched? Perhaps. But are they inherently *good* ideas? Are they even *possible*?

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The U.S. Department of Energy (DOE) was created, in part, to answer basic questions concerning energy research and development (R&D). Established in 1977 to manage the nation's nuclear weapons complex, clean up the ''environmental legacy'' from the production and testing of nuclear weapons, and conduct R&D on energy and basic science, the DOE is a behemoth organization dedicated to an overwhelmingly complicated task: provide ''the framework for a comprehensive and balanced national energy program.'' To meet its mission, the DOE controls a $23 billion budget, employs a workforce of 14,500 people and more than 100,000 contractors, and operates 50 major installations in 35 states. The DOE also directs a complex network of 24 national laboratories located in 14 states with an additional staff of 60,000 and a budget of $7.6 billion.[1]

Like all large institutions, the DOE has developed its own way of conducting research, and consequently its own research culture. The concept of culture has often taken specific institutional forms, such as the ''national culture'' of the state, the ''market culture'' of the economy, the ''organizational culture'' of the business firm, and the ''medical culture'' of doctors.[2] Indeed, Ludwig Fleck, Emile Durkheim, Thomas Kuhn, Derek de Sola Price, and Mary Douglas have long argued that different groups of scientists promote and believe in different cultural practices through ''thought collectives,'' ''paradigms,'' and ''invisible colleges.'' For these authors, true solidarity is possible only to the extent that individuals share the categories of their thought, contradicting the basic axiom that sovereign actors always behave rationally.[3] Karin Knorr-Cetina notes that:

> Science and expert systems are obvious candidates for cultural division; they are pursued by groupings of specialists who are separated from other experts by institutional boundaries deeply entrenched in all levels of education, in most research organizations, in career choices, in our general systems of classification.[4]

It follows, then, that country's national laboratories have their own unique styles of research based on ''external'' or ''non-scientific'' factors such as the availability of financial and human resources, safety and security protocol, geography, the personalities of managers, and political support.[5]

But is the DOE model of R&D working, at least for the long-term? The DOE has been responsible for leading the country in terms of basic research and managing thousands of individual programs. Notable inventions within the past 10 years include the bio-mechanical pancreas (which uses a chemical glucose sensor to help patients manage diabetes), thin-film photovoltaic modules for roofs, and green solvents used for the bioremediation of toxic substances. In parallel, the past 30 years have seen incredible advances in energy technologies, ranging from more effective wind turbines, aero-derivative natural gas turbines, and bioelectric generators to hydrogen powered vehicles, cogeneration units, clean coal systems and advanced nuclear reactors.

Yet, despite these gains, the DOE model does not appear to offer the nation an optimal strategy for assessing long-term, transformational risks that require creative, ''out-of-the-box'' thinking to handle them. An overly rigid management structure and loss of mission within the DOE continues to plague its programs and create inconsistencies in terms of a national energy policy. Various layers of stove-piping within and between the DOE and national laboratories continue to fracture collaboration between institutions and engender only slow, incremental progress on energy problems. Energy research and development continues to remain grossly under-funded in both the public and private sectors, greatly compromising the country's ability to address energy challenges and contributing to an overall loss of economic competitiveness. Each of these three trends—*inconsistent* short-term energy policies, *incrementalism* in the way the nation's scientists and engineers approach energy problems, and *inadequate* support of energy research and development—contributes directly to the country's energy *insecurity*, risking inflated energy prices, environmental degradation, and recurring energy crises.

To respond to these challenges, the country needs a new, independent organization within the DOE. The idea was first proposed in a 2006 National Academies report entitled *Rising Above the Gathering Storm*, which suggested that the DOE create an institution (called the Advanced Research Projects Agency-Energy, or ARPA-E) to sponsor transformational, creative research.[6] The proposal was drafted into legislation before the U.S. Senate (S. 2197—Protecting America's Competitive Edge [PACE] Act—Energy), but failed to pass in March 2006. Based on similar organizations within the U.S. Department of Defense and the intelligence community, an ARPA-E like institution would need to conceptualize the R&D

[1] See U.S. National Science Foundation, *Federal Funds for Research and Development: Fiscal Year 2003–2005* (Washington, DC: NSF, 2005), p. 48; U.S. Department of Energy, *Protecting National, Energy, and Economic Security with Advanced Science and Technology and Ensuring Environmental Cleanup: The Department of Energy Strategic Plan*, August, 2003, available at http://www.nti.org/e_research/official_docs/doe/doe080603.pdf; and U.S. General Accounting Office, *Department of Energy: Fundamental Reassessment Needed to Address Major Mission, Structure, and Accountability Problems* (Washington, DC: GAO-02-51, December, 2001), p. 5.

[2] See Andrew Abbott, *The System of Professions: An Essay on the Division of Expert Labor* (Chicago: University of Chicago Press, 1988).

[3] See Mary Douglas, *How Institutions Think* (Syracuse: Syracuse University Press, 1986); Ludwig Fleck, *Genesis and Development of a Scientific Fact* (University of Chicago, 1979); Thomas S. Kuhn, *The Structure of Scientific Revolutions* (University of Chicago, 1962); Thomas S. Kuhn, *The Essential Tension: Selected Studies in Scientific Tradition and Change* (University of Chicago, 1977); and Derek de Sola Price and Donald Beaver, ''Collaboration in an Invisible College,'' *American Psychologist* 21 (1966), p. 1011–1018.

[4] Karin Knorr-Cetina, *Epistemic Cultures: How the Sciences Make Knowledge* (Cambridge, MA: Harvard University Press, 1999), p. 2.

[5] See Hugh Gusterson, *Nuclear Rites: A Weapons Laboratory at the End of the Cold War* (University of California, 1996).

[6] National Academy of Sciences, *Rising Above the Storm: Energizing and Employing America for a Brighter Economic Future* (Washington, DC: National Academies Press, 2006).

process differently than the DOE. It would have to be mission-oriented to focus on long-term, creative, transformational research and subscribe to an entirely different management philosophy.

The complete dependence of our modern culture on energy places it at a nexus of important concerns related to progress and modernity, nationalism, agriculture, industry, human needs and the environment. Yet while energy policy is indeed the primary focus of this investigation, do not be lulled into thinking that such an inquiry is just about energy. Assessing DOE research methods provides insight into how many of the country's best engineers and scientists conceptualize technology and innovation. Practitioners paint the national laboratories as a hot bed of innovation, where scientists and engineers rationally pursue the best scientific projects based on merit and fecundity.

Contrary to this view, social attitudes, interests, and values intricately shape DOE R&D agendas, which in turn mold technologies that profoundly shape society to better match those interests. The research system, as currently structured, not only condones small, incremental development but also actively encourages it. Program managers, more often than not, subtly prevent radical and progressive change, and innovative ideas regarding energy technologies are often subverted, or worse, ignored. In this way, the difficulties in motivating the DOE to conduct transformational research threaten to surface wherever large institutions attempt to produce knowledge, patronage complicates the R&D process, and the boundaries between science, technology, and society are being negotiated. The lessons here are not just for energy policymakers and research managers, but for anyone concerned with the difficulties of managing large, centralized networks of scientists and investigators, ranging from those working in the fields of aerospace and defense to biotechnology, pharmaceuticals, and telecommunications.

Ultimately, clashes over the optimal R&D pathway at the DOE and its national laboratories are preludes to a deeper clash about technological systems, or about what type of society we want to build. What seem on the surface to be merely technical debates over the different segments of an R&D strategy are also subtle and often invisible contests over social ideology. Donald MacKenzie reminds us that technological systems ''should not be taken simply as given, as unproblematic features of the world; nor should the use of the term 'system' be taken to imply stability or lack of conflict. Systems are constructs and hold together only so long as the correct conditions prevail.''[7] Therefore, the way that DOE research on energy technology redistributes social, political, and economic power is as important as how efficiently such technologies actually produce energy. It should come as no surprise, then, that the existing R&D pathways at the DOE surreptitiously impede radical change.

[7] Donald MacKenzie, ''Missile Accuracy: A Case Study in the Social Process of Technological Change,'' In: Wiebe Bijker, Thomas P. Hughes, and Trevor Pinch (Eds.) *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology* (London: MIT Press, 1987), p. 197.

## 2. The three ''I's'' of the American energy impasse

### 2.1. Inconsistency

Contrary to a historical role as an incubator of energy technologies and a supporter of scientific research, the DOE and its national laboratories have been recently criticized for losing their sense of mission and ineffective management. DOE labs are said to be the most lacking in flexibility and cost effectiveness, resulting from an overly centralized, hierarchical and micromanaged resource allocation system.[8] Such criticism is usually based on three grounds: that the DOE's diverse mission creates an uncoordinated approach to energy problems; loss of mission is further compounded by a dysfunctional organizational structure; and as a result DOE research remains hindered by a weak culture of accountability.

As an example, the complicated nature of managing the nation's nuclear stockpile, cleaning up environmentally hazardous waste, and conducting basic and energy research have made programs within the DOE difficult to integrate. Separate energy, environmental, science, and national nuclear security staff tend to operate as isolated entities, each with their own operational styles and decision-making practices. This is affected partly by managerial style (some exercise strong central control over programmatic actions, others delegate responsibility) and partly by area of expertise (national security programs operate in secret, science programs attempt to be more open).[9] A 2003 Secretary of Energy task force assessing DOE science programs concluded that, as a result, ''the mission of the Department of Energy is widely misunderstood and considered to be unclear and unstable'' and the budgets of the national laboratories suffer from a historically poor reputation as ''badly managed, excessively fragmented, and politically unresponsive.''[10] Another influential report concluded that ''there is neither an overarching strategic vision integrating and ensuring the comprehensiveness of the array of federal activities on energy research, development, and demonstration cooperation nor a mechanism for implementing such a vision in a coherent and efficient way.''[11] Similarly, the Committee on Economic Development expressed concern about ''mission creep in those sectors of the basic research establishment—particularly certain of the Department of Energy's national laboratories—that have completed or lost their mandates.''[12]

[8] Kenneth M. Brown, *Downsizing Science: Will the United States Pay a Price?* (Washington, DC: American Enterprise Institute Press, 1998).

[9] U.S. General Accounting Office, *Department of Energy: Fundamental Reassessment Needed to Address Major Mission, Structure, and Accountability Problems* (Washington, DC: GAO-02-51, December, 2001).

[10] Secretary of Energy Advisory Board, *Critical Choices: Science, Energy, and Security* (Final Report of the Task Force on the Future of Science Programs at the Department of Energy), October 13, 2003, p. 12–15.

[11] John P. Holdren et al., *Powerful Partnerships: The Federal Role of International Cooperation on Energy Innovation* (Washington, DC: Office of Science and Technology Policy, 1999), p. ES-5.

[12] Committee on Economic Development, *America's Basic Research: Prosperity Through Discovery* (Washington, DC: CED, 1998), p. 2.

The lack of such vision only increases the likelihood that DOE grant solicitations will not match programmatic need.

Furthermore, the DOE suffers from an exceedingly complicated organizational structure connected to the sheer challenge of coordinating their vast network of field offices and national laboratories widely dispersed throughout the country. Within each individual organization, multiple levels of reporting exist vertically between management, group leaders, and research associates, and horizontally between the DOE, other laboratories, operations offices, and headquarters program offices. Unclear chains of command, weak integration of programs and functions, and confusion over staff roles remain common. In 1999, the Special Investigative Panel of the President's Foreign Intelligence Advisory Board noted that ‘‘convoluted, confusing, and often contradictory reporting channels have made the relationships between DOE headquarters and the laboratories, in particular, tense, internecine, and chaotic.''[13]

The implications of this lack of coordination are manifold. Disharmony makes it difficult to detect inconsistencies within individual programs and almost impossible to coordinate the national laboratories to meet pressing nation-wide problems; programs instead tend to operate on a case-by-case basis. Applied research programs tend to be organized around fuel sources, such as coal, oil, nuclear, and natural gas, which increases the risk of isolating oil supply from transportation or fossil fuels from efficiency. Such isolation, in turn, promotes a tendency to focus on incremental or discrete technologies as opposed to systems that integrate research needs from supply to distribution to end use. Melanie Kenderline, Vice President for the Gas Technology Institute, argues that ‘‘in the final analysis, competition for funding from the same appropriation, bureaucratic separation, and different program cultures and performance measures ultimately work against optimum levels of cooperation and coordination across programs [at the DOE].''[14] Similarly, Jerome Hinkle recently told senators that ‘‘it is unlikely that a traditional federal agency structure could accomplish blending the necessary functions [to distribute promising technologies,] because they are often assigned to completely separate programs whose cooperation is incidental.''[15]

Moreover, poor coordination makes it challenging to track and enforce laboratory reforms. A 2001 report from the National Resource Council assessing DOE research and development on energy technologies from 1978 to 2000 noted that ‘‘managers of both the energy efficiency and fossil energy research, development, and demonstration programs [at the Department of Energy] did not utilize a consistent methodology or framework for estimating and evaluating the benefits of the numerous projects within their programs.''[16] Similarly, a 2000 report from the National Academies reviewing U.S. Department of Energy's renewable energy programs found that ‘‘Office of Power Technology's programs are not well integrated or coordinated but have operated as relatively separate groups with no common policy focus.''[17] The 2000 National Academies report also accused DOE energy programs of having insufficient strategic planning and analysis, poor R&D project selection, inability to learn lessons from past failures, and weak coordination with other government agencies.[18] And a 1998 GAO report noted that the Department of Energy's national laboratories were ‘‘unfocused, micromanaged, and do not function as an integrated national research and development system.''[19] The GAO accused the labs of duplicating private research, conducting programs that were fragmented and unrelated to the overall mission of the DOE, and an overall loss of coherence and effectiveness.

The aforementioned problems relating to loss of mission and confusing organizational structure have promoted a weak culture of accountability. Poorly performing contractors and staff are rarely held accountable for mistakes, and ‘‘mission creep'' often complicates the termination of unsuccessful programs. For example, the Galvin Task Force was commissioned in 1995 by Secretary of Energy Hazel O'Leary to produce a 10-month study on the national laboratories. Their report concluded that ‘‘research culture at many of the laboratories has been influenced by their relative physical and intellectual isolation and by a sense of entitlement to research funds.''[20] Because project managers tend only to work on their projects, they tend to self-perpetuating. As Ronald J. Sutherland and Jerry Taylor put it, ‘‘program goals are more likely to be technical than economic, and program managers are technical optimists about their own programs.''[21]

A similar Brookings Institution study found that DOE managers are therefore more likely to be risk averse, and that the ‘‘overriding lesson'' about the national laboratories is that they remain ‘‘so severely constrained by political forces that an effective, coherent national commercialization R&D program

[13] Special Investigative Panel of the President's Foreign Intelligence Advisory Board, *Science At Its Best, Security At Its Worst: A Report on Security Problems at the U.S. Department of Energy*, 1999, available at http://www.hanford.gov/oci/maindocs/ci_r_docs/sciencebest.pdf.

[14] Melanie Kenderdine, ‘‘Should Congress Establish ARPA-E?'' *Statement Before the Committee on Science, U.S. House of Representatives*, March 9, 2006, p. 4–5.

[15] Jerome Hinkle, ‘‘Assessing Progress in Advanced Technologies for Vehicles and Fuels,'' *Testimony Before the House Committee on Science*, June 5, 2006, p. 10–11.

[16] National Resource Council, *Energy Research at DOE: Was it Worth It? Energy Efficiency and Fossil Energy Research 1978–2000* (Washington, DC: National Academies Press, 2001), p. 7.

[17] Committee on Programmatic Review of the U.S. Department of Energy's Office of Power Technologies, *Renewable Power Pathways: A Review of the U.S. Department of Energy's Renewable Energy Programs* (Washington, DC: National Academies Press, 2000), p. 3.

[18] Ibid., p. 92–101.

[19] U.S. General Accounting Office, *Department of Energy: Uncertain Progress in Implementing National Laboratory Reforms* (Washington, DC: GAO/RCED-98-197, September, 1988), p. 1.

[20] Secretary of Energy Advisory Board, *Alternative Futures for the Department of Energy National Laboratories* (Washington, DC: Task Force on Alternative Futures for the Department of Energy National Laboratories, 1995), p. 41.

[21] Ronald J. Sutherland and Jerry Taylor, ‘‘Time to Overhaul Federal Energy R&D,'' *Policy Analysis* 424 (February 7, 2002), p. 7.

has never been put in place."[22] For instance, according to the GAO, the DOE has only once—at Brookhaven National Laboratory in 1997—fired a contractor for poor performance. Inflated staffing levels, in turn, complicate the ability to recruit and hire more qualified engineers and scientists. Prominent examples of programs that continued to receive funding long after they were determined technologically unfeasible include the Clinch River Breeder Reactor (a $2.5 billion demonstration liquid–metal fast breeder reactor plant), magnetohydrodynamics program (a $61 million fossil energy program attempting to use electromagnetic induction to produce electric power from coal), and the creation of the Synfuels Corporation (a $2.1 billion synthetic fuels program established in 1981 to develop alternatives to oil).[23]

### 2.2. Incrementalism

In addition to promoting inconsistency, the DOE, and to a degree most American research institutions, "stove-pipes" research in at lease two ways: by relying on a linear, "assembly-line" model that segregates the stages of R&D; and by training scientists and engineers exclusively as "problem solvers," which contributes to them "working within the system" rather than challenging its fundamental assumptions.

Almost since the beginning of the 20th century, scientists, industrialists, researchers, managers, politicians, statisticians, and economists—along with universities, national laboratories, and organizations such as the National Science Foundation, National Research Council, and Organization for Economic Cooperation and Development—have subscribed to a linear, assembly line model of technological development. Such a model sharply divides research into stages, such as "basic" and "applied" research, "development," and "innovation." Whatever its name, the model has been "the very mechanism used for explaining innovation in the literature on technological change and innovation since the 1940s."[24]

The linear model of innovation gained popularity in the 1910s and 1920s, when academic and industrial natural scientists conceived of basic research as the source behind applied research and technology. It was during this phase that the ideal of pure science was articulated as a method of research performed without commercial or practical ends, a form of inquiry that benefits all of society and the good of humanity. Basic research was held to be distinct from applied science, a method directed towards practical or commercial gain, or the use of science to achieve some specific purpose or objective. Put another way, applied science is "pure science applied," or:

> The applied scientist as such is concerned with the task of discovering applications for pure theory. The technologist has a problem which lies a little nearer to practice. Both applied scientist and technologist employ experiment; but in the former case guided by hypotheses deduced from theory, while in the latter case employing trial and error or skilled approaches derived from concrete experience.[25]

Vannevar Bush subscribed to this type of thinking in his seminal *Science: The Endless Frontier*, where he equated college and university research as "basic" and industrial or government research as "applied." According to Bush:

> Basic research leads to new knowledge. It provides scientific capital. It creates the fund from which the practical applications of knowledge must be drawn. New products and new processes do not appear full-grown. They are founded on new principles and new conceptions, which in turn are painstakingly developed by research in the purest realms of science. Today, it is even truer that basic research is the pacemaker of technological progress.[26]

Such thinking develops a causal relationship between basic and applied research, placing the former as the foundation for scientific progress.

The notions of "development" and "innovation" were added to the linear model in the 1950s and 1960s. Business school researchers studying industrial management of R&D noted that "development" was often needed to take a new process or product from the laboratory to the stage where it was ready to manufacture on a large scale, or translating applied research findings into products and processes. Economists extended the three-phase model of basic research → applied research → development to production and diffusion under the concept of "innovation."[27]

In practice, such idyllic thinking compliments the way most DOE practitioners conceive of science, and is often used to justify rigid distinctions between basic research, applied research, and technological development.[28] Engineers and

[22] Linda R. Cohen and Roger G. Noll, *The Technology Pork Barrel* (Washington, DC: Brookings Institution, 1991), p. 378.

[23] Kelly Sims Gallagher, Robert Frosch, and John P. Holdren, "Management of Energy Technology Innovation Activities at the U.S. Department of Energy," *Report to the Belfer Center for Science and International Affairs*, September, 2004, available at http://bcsia.ksg.harvard.edu.

[24] Benoit Godin, "The Linear Model of Innovation: The Historical Construction of an Analytical Framework," *Science, Technology, & Human Values* 31(6) (November, 2006), p. 641.

[25] James K. Feibleman, "Pure Science, Applied Science, and Technology: An Attempt at Definitions," In: Carl Mitcham and Robert Mackey (Eds.) *Philosophy and Technology: Readings in the Philosophical Problems of Technology* (London: The Free Press, 1983), p. 36.

[26] In Edwin Layton, "Mirror-Image Twins: The Communities of Science and Technology in 19th-Century America," *Technology and Culture* 12(4) (October, 1971), p 563.

[27] See Benoit Godin, "The Linear Model of Innovation: The Historical Construction of an Analytical Framework," *Science, Technology, & Human Values* 31(6) (November, 2006), p. 639–667.

[28] For excellent investigations of the historical development of such distinctions between basic and applied science and the role of government in scientific research, see Bruce Smith, *American Science Policy Since World War II* (Washington, DC: Brookings Institution, 1990); A. Hunter Dupree, *Science in the Federal Government: A History of Policies and Activities* (Baltimore: Johns Hopkins University Press, 1986); Daniel Lee Kleinman, *Politics on the Endless Frontier: Postwar Research Policy in the United States* (London: Duke University Press, 1995); David M. Hart, *Forged Consensus: Science, Technology, and Economic Policy in the United States, 1921–1953* (Princeton, NJ: Princeton University Press, 2000); and Daniel J. Kevles, "The National Science Foundation and the Debate over Postwar Research Policy, 1942–1945," *ISIS* 68(241) (1977), p. 5–26.

scientists working at the national laboratories often conclude that technology and technological development progress in a rational, ordered, and predictable manner. They see science and technology as an assembly line that begins with basic research, follows with development and marketing of a given technology, and ends with the product being purchased by consumers.[29] Such thinking structures technological development and diffusion into at least four separate levels: (1) a basic research phase; (2) an applied research or invention phase, in which other engineers actually create artifacts in laboratories, apply for patents, model the prototype, and test it; (3) a market phase, in which technology is then passed onto salespeople and managers; before (4) a consumption phase, in which technology is sold to the public, consumed, and perhaps modified by users. Put simply, the assembly line model suggests that engineers and scientists design technology, manufacturers produce it, salespeople sell it, and users use it.[30]

The ''assembly-line model'' of technical development holds immense appeal for scientists, engineers, managers, and policymakers for five reasons. First, it seems to explain the nature of technological development during World War II—where scientific research was conducted under the auspices of the military, and the diffusion of technology tended to occur along a linear pathway. Second, it served as a powerful rhetorical resource for various disciplinary groups attempting to establish, define, demarcate, or maintain their power over technological development. Scientists often referenced the model to justify financial support for projects; engineers to raise the status of their discipline; and industrialists to attract workers to their research organizations. Third, the model assuages a general wariness among scientists towards intrusive industrial policy, since the assembly-line model posits that technological diffusion is more or less automatic and unmanaged—and should thus be controlled by scientists rather than the state. Fourth, the model helps soften mainstream political fears of a loss of technological competitiveness, as it suggests a certain level of funding in ''basic science'' will always yield plentiful technological results.[31] And fifth, the model is attractive in its simplicity. Alternative models of diffusion—with their multiple feedback loops and triple helixes of knowledge dissemination—are perceived to be overly complicated, looking more like ''modern artwork'' or a ''plate of spaghetti and meatballs'' than useful descriptive frameworks.[32]

A research strategy for supporting novel energy technologies, the thinking goes, becomes relatively simple. Merely provide enough funding and support for basic research, and if a technology is truly possible, it can be developed by scientists and then diffused into the marketplace, where rational actors will seek to fully exploit its promise. Under this system, the role of the DOE is to support basic scientific research that industry will not. The model made perfect sense in an era characterized by mass production, expanding national markets, complicated but connected factory systems, and economies of scale. Susan Hockfield explains that ''the corporations that dominated that economy were interested in incremental rather than radical innovation; technology was not intended to be, as we now put it, 'disruptive;' and we built great industry lab systems to support incremental innovation.''[33]

Now, however, distinctions between basic and applied science have become so blurred that the model no longer makes sense.[34] The historical record seems to disprove any sharp distinction between basic and applied research. Otto Mayr argues that such boundaries remain incongruent because many ''scientists'' such as William Thompson the Baron of Kelvin, Galileo Galilei, and Gottfried Leibniz became famous as contributors to technology, yet many ''engineers'' such as Leonardo da Vinci and James Watt became famous in science. Mayr suggests that:

> The words 'science' and 'technology' are useful precisely because they serve as vague umbrella terms that roughly and impressionistically suggest general areas of meaning without precisely defining their limits. Most successfully the words are used in conjunction; 'science and technology' together refer to an entity that actually exists in our civilization but which is impossible to divide into two parts, 'science' and 'technology.' Within this whole the two words only set accents, referring to two sets of general styles and approaches that are contrasting as well as complimentary.[35]

The only benefit of distinguishing between types of basic and applied research, Mayr concludes, is the strategic flexibility the terms offer in supporting each other.

Indeed, history is replete with instances of technologies that have emerged without preceding theoretical work in science. As one classic example, consider the work of D.S.L. Cardwell on 18th century power technologies. Cardwell argues that steam engines emerged as successful technologies more than a century before the science of thermodynamics became formulated.[36] David Nye notes that changes in barometric pressure in early coal mines were suspected before they could

[29] Brian Elliott, ''Introduction,'' In: Brian Elliott (Ed.) *Technology and Social Process* (Edinburgh: Edinburgh University Press, 1988), p. 3; George Wise, ''Science and Technology,'' *Osiris* 1 (1985), p. 229.

[30] Wiebe Bijker, ''The Social Construction of Fluorescent Lighting, or How an Artifact Was Invented in its Diffusion Stage,'' In: Wiebe Bijker and John Law (Eds.) *Shaping Technology/Building Society: Studies in Sociotechnical Change* (Cambridge, MA: MIT Press, 1992), p. 76.

[31] See David H. Guston, ''Stabilizing the Boundary between US Politics and Science: The Role of the Office of Technology Transfer as a Boundary Organization,'' *Social Studies of Science* 29(1) (February, 1999), p. 87–111, especially 93–94.

[32] Benoit Godin, ''The Linear Model of Innovation: The Historical Construction of an Analytical Framework,'' *Science, Technology, & Human Values* 31(6) (November, 2006), p. 660.

[33] Susan Hockfield, ''The University in the U.S. Innovation System,'' *Presentation at the Bernard L. Schwartz Forum on U.S. Competitiveness in the 21st Century*, Brookings Institution, Washington, DC, April 26, 2006, available at http://web.mit.edu/hockfield/speech-brookings.html.

[34] Everett Mendelsohn, ''Science, Scientists, and the Military,'' In: John Krige and Dominique Pestre (Eds.) *Science in the Twentieth Century* (London: Harwood Academic Publishers, 1997), p. 176.

[35] Otto Mayr, ''The Science-Technology Relationship as a Historiographic Problem,'' *Technology and Culture* 17(4) (October, 1976), p. 668–669.

[36] D.S.L. Cardwell, ''Power Technologies and the Advance of Science, 1700–1825,'' *Technology and Culture* 6(2) (Spring, 1965), p. 188–207.

be explained scientifically.[37] Semiconductor electronics existed before the specifics of semiconductor physics were fully comprehended.[38] Thus, Derek De sola Price is quick to reject that technology is applied knowledge, stating that "inventions do not hang like fruits on a scientific tree."[39] Instead, technologies emerge in a nonlinear and unpredictable fashion that depends deeply on the way that a system challenges, rearranges, or supports social and technical arrangements.

Additionally, distinctions between the stages of R&D appear to be more a product of human interpretation rather than historical fact or natural law. In the 1960s the Department of Defense commissioned Project Hindsight in an attempt to better understand the technological R&D process. Project Hindsight took 8 years to complete and employed forty people to analyze some 700 contributions or "events" resulting from science and technology in an attempt to better distinguish basic research, applied research, and technology. Surprisingly, the study found that 91% of events were considered "technological," with only 9% classified as "science." And of that 9%, only 0.3% was considered "basic research."[40] Thus, the study suggests that the unidirectional relationship posited by the assembly line model is unable to fully explain the course of technological development and innovation.

Furthermore, a second form of "stove-piping" relates to how most scientists and engineers are trained to think as "problem solvers." The American engineering profession became formulated in an early context in which national progress had come to be measured in terms of the private-sector production of low cost goods for mass consumption.[41] As American engineering practices gained association with mass industrial production, practitioners continued to narrow the engineering field to focus only on core technical issues relating to science and technology.[42] The American response to Sputnik in 1960s and 1970s redefined this technical core to include science-based problem solving for society's needs. Everything else was relegated as a "soft skill" and set to the periphery.[43]

However, defining engineering in this way conditions engineers to become problem solvers but not problem definers. Gary Downey and Juan Lucena elaborate that:

> As students become transformed into engineering problem solvers, what gets weeded out is everything else. That is, engineering students experience a compelling demand to separate the work part of their lives from the non-work parts. Work is about rigorously applying the engineering method to gain control over technology and is simply not about any other stuff. Budding engineers can have the other stuff in their lives, but not in their practices as engineers.[44]

Problem solving is judged to be wholly technical (and thus within the exclusive field of engineering), whereas defining and assessing problems is said to be non-technical, and therefore unimportant.[45] As Ken Adler put it, "The immediate purview of engineering is technological design ... In this sense, engineering denies history. It has no sympathy with the conflict, compromise, and happenstance that brought the world to its present state."[46] In other words, engineers are trained to think in terms that bias the present, and presume that technological development is synonymous with progress.

Consequently, American engineers are supposed to respond to calls from society "much like a consultant responds to clients."[47] This disciplines them to a method that draws sharp boundaries between social problems and technical solutions. The result is that most engineers think narrowly in terms of their area of expertise; they think in incremental rather than progressive terms; and they solve problems that they are assigned, rather than thinking creatively and devising transformational research solutions. Joe Loper argues that since big, revolutionary projects at the DOE are structurally impossible, "only small things are doable, so you end up with a bunch of little doable policies that will result in no real impact."[48] Thomas Petersik, a former

[37] David Nye, *Consuming Power: A Social History of American Energies* (Cambridge, MA: MIT Press, 1999), p. 86.

[38] Susan Hockfield, "The University in the U.S. Innovation System," *Presentation at the Bernard L. Schwartz Forum on U.S. Competitiveness in the 21st Century*, Brookings Institution, Washington, DC, April 26, 2006, available at http://web.mit.edu/hockfield/speech-brookings.html.

[39] Derek J. de S. Price, "The Parallel Structures of Science and Technology," In: Barry Barnes and David Edge (Eds.) *Science in Context: Readings in the Sociology of Science* (London: Open University Press, 1982), p. 169–170.

[40] Edwin Layton, "Mirror-Image Twins: The Communities of Science and Technology in 19th-Century America," *Technology and Culture* 12(4) (October, 1971), p. 564.

[41] See Gary Downey, "Are Engineers Losing Control of Technology? From Problem Solving to Problem Definition and Solution in Engineering Education," *Chemical Engineering Research and Design* 83(6) (2005), p. 585; and Eda Kranakis, *Constructing a Bridge: An Exploration of Engineering Culture, Design, and Research in Nineteenth-Century France and America* (Cambridge, MA: MIT Press, 1997).

[42] See David Hounshell, *From the American System to Mass Production, 1800–1933: The Development of Manufacturing Technology in the United States* (Baltimore: Johns Hopkins University Press, 1984); David F. Noble, *Forces of Production: A Social History of Industrial Automation* (New York: Alfred Knopf, 1984); Thomas J. Misa, *A Nation of Steel: The Making of Modern America, 1865–1925* (Baltimore: Johns Hopkins University Press, 1995); and Gary Downey and Juan Lucena, "When Students Resist: Ethnography of a Senior Design Experience in Engineering Education," *International Journal of Engineering Education* 19(1) (2003), p. 168–176.

[43] See, for instance, National Academy of Engineering, *The Engineer of 2020: Visions of Engineering in the New Century* (Washington, DC: National Academies Press, 2004), p. 43.

[44] Gary Lee Downey and Juan C. Lucena, "Engineering Selves: Hiring into a Contested Field of Education," In: G. L. Downey and J. Dumit (Eds.) *Cyborgs and Citadels: Interventions in Emerging Sciences and Technologies* (Sante Fe, NM: School of American Research Press, 1997), p. 128.

[45] See Gary Downey and Juan Lucena, "Are Globalization, Diversity, and Leadership Variations of the Same Problem? Moving Problem Definition to the Core," *Distinguished Lecture to the American Society for Engineering Education*, Chicago, Illinois, available at http://www.asee.org/chicago2006/.

[46] Ken Adler, *Engineering the Revolution: Arms and Enlightenment in France, 1763–1815* (Princeton, NJ: Princeton University Press, 1997), p. 15.

[47] Gary Downey, "Are Engineers Losing Control of Technology? From Problem Solving to Problem Definition and Solution in Engineering Education," *Chemical Engineering Research and Design* 83(6) (2005), p. 586.

[48] In Benjamin K. Sovacool, *The Power Production Paradox: Revealing the Socio-technical Impediments to Distributed Generation Technologies* (Blacksburg, VA: Virginia Tech, Doctoral Dissertation, April 17, 2006), p. 164, available at http://scholar.lib.vt.edu/theses/available/etd-04202006-172936/, p. 260.

analyst for the U.S. Energy Information Administration, adds that American energy policy can best be characterized by "a series of baby steps in many directions, carefully avoiding any fundamental movements on anything."[49]

### 2.3. Inadequacy

In addition to inadvertently condoning inconsistency and incrementalism in its research, the federal government continues to under-fund energy and science R&D. The American Association for the Advancement of Science reports that federal funding of research in the physical sciences as a percentage of the country's gross domestic product (GDP) was 45% less in 2004 than in 1976.[50] A similar National Academies report noted that federal funding for environmental sciences, physical sciences, mathematics and engineering shrank from more than 15% (in real terms) from 1994 to 2003.[51] From 1985 to 1994, total U.S. expenditures on energy R&D decreased from $7 billion per year to $5 billion (in 1995 dollars). During that time, the federal government invested only approximately 3% of total R&D expenditures on energy, even though energy industries contribute more than 8% to the country's gross domestic product.[52] And while federal R&D in technology reached $132 billion in 2005, it continued to be concentrated in the fields of defense, homeland security, and the space program (See Fig. 1).[53]

Federal funding for R&D in efficiency measures, distributed generation, and renewable energy technologies, for instance, have declined as a portion of real gross domestic product by more than 70% over the past 10 years.[54] After funding for such technologies peaked in 1980 at $1.3 billion, it declined to $560 million in 1980 and just under $140 million in 1990, after which funding stabilized at around $200 million (see Figs. 2 and 3).

As Kurt Yeager, former president of the Electric Power Research Institute, remarked, "Today the United States invests at a lower rate than its major international competitors ... Federal energy-related R&D has declined significantly."[55]

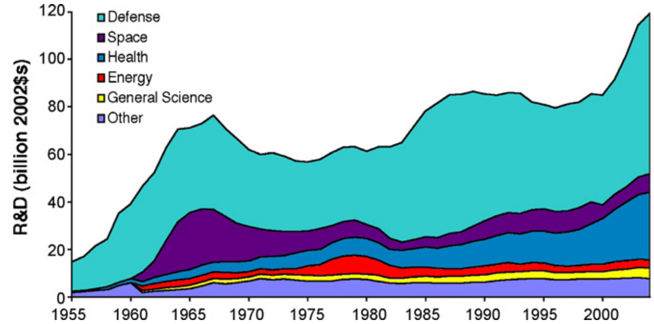


Fig. 1. U.S. Federal Research and Development, 1955–2004[93].

[93] Source: Robert M. Margolis and Daniel Kammen, "Underinvestment: The Energy Technology and R&D Policy Challenge," *Science* 285(5428), p. 690–692. Used with permission.

This decline in public support for energy research and development has continued even though multiple studies have shown that the benefits of R&D in the energy sector far outweigh its costs. For instance, Robert N. Schock et al. estimate just the *insurance* value of energy R&D per year (in 1999 dollars)—the contribution of research towards fighting climate change, minimizing oil price shocks, fighting urban air pollution, and minimizing energy disruptions—at more than $12 billion, even though it cost the government only $1.5 billion.[56]

Recent events in the energy sector—such as the restructuring of the electric utility industry and increased competition—make it unlikely that the industry will be able to compensate for public underinvestment. Restructuring of the electric utility industry and the repeal of the Public Utilities Holding Company Act of 1935 (PUHCA) has only increased the incentive for companies and firms to invest in short-term technologies with rapid financial returns. A 1999 Office of Science and Technology Policy report cautioned that:

> Privatization, deregulation, and restructuring of energy industries ... can lead to neglect of the ways the composition and operation of energy systems affect the wider public interest (including meeting the basic needs of the poor, as well as addressing other macroeconomic, environmental, and international security needs). [57]

A resulting gap between what the private sector does and what society's interests require continues to emerge.

As a result, energy R&D *intensity*—expenditures for energy R&D as a percentage of the utility's total sales for 1 year—among energy companies averages 0.3%, compared to an average industrial benchmark of 3.1%. The U.S. National Association of Regulatory Utility Commissioners has traditionally recommended that utilities devote at least 1.0% of their

[49] Ibid, p. 289.

[50] American Association for the Advancement of Science, *Trends in the Federal Research by Discipline, FY 1976-2004*, available at http://www.aaas.org/spp/rd/discip04c.pdf.

[51] National Academies, *Engineering Research and America's Future: Meeting the Challenges of a Global Economy* (Washington, DC: National Academies Press, 2005).

[52] Robert N. Schock et al., "How Much is Energy Research & Development Worth as Insurance?" *Annual Review of Energy and Environment* 24 (1999), p. 488.

[53] Adam Segal, "Is America Losing Its Edge? Innovation in a Globalized World," *Foreign Affairs* 83(6) (2004), p. 2–8.

[54] See Woodrow Clark and William Isherwood, "Distributed Generation: Remote Power Systems With Advanced Storage Technologies," *Energy Policy* 32 (2004), p. 1573–1589; S. Julio Friedman and Thomas Homer-Dixon, "Out of the Energy Box," *Foreign Affairs* 83(6) (2004), p. 72–83.

[55] Kurt E. Yeager, "Electricity Deregulation and Implications for R&D and Renewables," *Hearing Before the Subcommittee on Energy and Environment of the House Committee on Science*, March 31, 1998, p. 57.

[56] Robert N. Schock, William Fulkerson, Merwin Brown, Robert San martin, David Greene, and Jae Edmonds, "How Much is Energy Research & Development Worth as Insurance?" *Annual Review of Energy and Environment* 24 (1999), p. 487–512.

[57] John P. Holdren et al., *Powerful Partnerships: The Federal Role of International Cooperation on Energy Innovation* (Washington, DC: Office of Science and Technology Policy, 1999), p. ES-4.

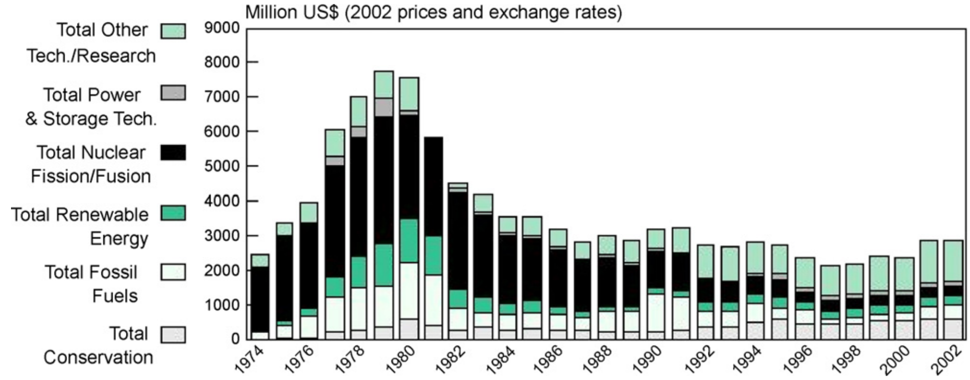


Fig. 2. U.S. Government Research and Development on Energy Technologies, 1974–2002[94].

[94] Source: International Energy Agency, *Renewable Energy RD&D Priorities: Insights from IEA Technology Programs* (Paris: OECD Publishing, 2004), p. 646. Figure used with permission.

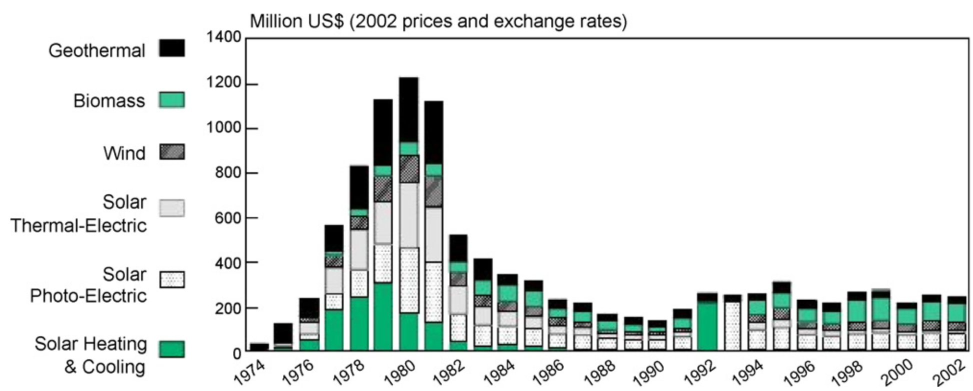


Fig. 3. U.S. Government Research and Development on Renewable Energy, 1974–2002[95].

[95] Source: International Energy Agency, *Renewable Energy RD&D Priorities: Insights from IEA Technology Programs* (Paris: OECD Publishing, 2004), p. 646. Figure used with permission.

sales to energy R&D.[58] Yet increased competition means that companies are likely to make investments only in short-term products that have better discount rates, lower risk, and perceived better financial return to the company's investors. It also means that, in order to prepare for competition, many utilities cut investment in discretionary spending. Because restructuring generally attempts to eliminate rate of return regulation and integrated resource planning with price caps, it further decreases the incentive for utilities to conduct energy research and development.[59]

For instance, during the late 1990s, utilities drastically cut R&D spending on energy technologies to prepare for restructuring and impending competition. A 1998 study conducted by the U.S. Government Accountability Office (GAO) concluded that ‘‘increased competition from restructuring was cited as the primary reason for the biggest cutbacks in research to date by utilities in California, New York, and Florida.’’[60] The revocation of PUHCA could accelerate this trend, since the financial consolidation of utilities and holding companies will likely convince utilities to shift the focus of their R&D from collaborative projects benefiting society to proprietary R&D giving their affiliates a competitive edge. Empirically, the GAO has noted that when utilities must consolidate, the result is ‘‘slowing technology development, sacrificing future prosperity to meet short-term goals, and failing to meet national energy goals.’’[61] Or, as Robert Margolis

[58] J.J. Dooley, ‘‘Unintended Consequences: Energy R&D in a Deregulated Energy Market,’’ *Energy Policy* 26(7) (1998), p. 547–555.

[59] See Benjamin K. Sovacool, ‘‘PUHCA Repeal: Higher Prices, Less R&D, and More Market Abuses?’’ *Electricity Journal* 19(1) (January/February, 2006), p. 85–89; Steve Nadel and Marty Kushler, ‘‘Public Benefits Funds: A Key Strategy for Advancing Energy Efficiency,’’ *Electricity Journal* 13(10) (October, 2000), p. 76.

[60] In Victor S. Rezendes, ‘‘Electricity Deregulation and Implications for R&D and Renewables,’’ *Hearing Before the Subcommittee on Energy and Environment of the House Committee on Science*, March 31, 1998, p. 97.

[61] Ibid, p. 94–107.

and Daniel Kammin put it succinctly, "the energy sector dangerously underinvests relative to other technology intensive sectors of the economy."[62] R&D investments made by all energy companies, for instance, have declined 50% between 1991 and 2003.[63]

Subsequently, indicators confirm that the nation's economic competitiveness is deteriorating. According to the U.S. National Science Foundation, in 2001 the country became a net importer of advanced technologies. The nation's trade balance in high technology products—computers, office equipment, chemicals, communication equipment, electronic components, instruments, and data processing services—shifted from a positive $54 billion in 1990 to negative $50 billion in 2001.[64] Furthermore, from June 2005 to June 2006, the United States suffered a trade deficit of approximately $814.7 billion.[65] Data from the Organization for Economic Cooperation and Development marked 2005 as the first year that Japan, Finland, and Sweden surpassed the United States as the world leader in terms of research and development intensity—the amount the country spends as a whole on research compared to GDP.[66] Richard M. Jones from the American Institute of Physics put it simply by noting that:

> As a result, Europe and Asia are threatening America's dominance in the physical sciences as measured by the number of patents won, articles submitted to scientific journals, degrees awarded, Nobel prizes won, or the percentage of GDP dedicated to research and development. Furthermore, test scores show that American youth, as they progress through the education system, fall further and further behind their counterparts in other counties, especially when it comes to math and science.[67]

This could be why the *New York Times* reported in 2004 that low-wage employers like Wal-Mart and McDonald's (who tend to pay unskilled workers $8 an hour) created 44% of the country's new jobs, whereas high-wage employers (who tend to pay educated workers more than $25 an hour) created only 29% of new jobs.[68] Robert Blecker, an economist at American University, summed it up concisely by stating that "in recent decades, the United States position has eroded on every front. The U.S. has clearly lost its unique dominance in the field of technological innovation."[69]

The collective result of diminishing private and public research is an inevitable crisis of economic competitiveness. Norman Augustine, former Chief Executive Officer of Lockheed Martin, told senators in 2005 that "it is the unanimous view of our committee that America today faces a serious and intensifying challenge with regard to its future competitiveness and standard of living. Further, we appear to be on a losing path."[70] The American Electronics Association reached a similar conclusion when they stated that:

> We are slipping. Yes, the United States still leads in nearly every way one can measure, but that does not change the fact that the foundation on which this lead was built is eroding. Our leadership in technology and innovation has benefited from an infrastructure created by 50 years of continual investment, education, and research. We are no longer maintaining this infrastructure.[71]

Correspondingly, the country faces an urgent need for high quality research and development in basic science and energy—two core areas of the DOE. The National Academy of Sciences (2005) recently concluded that "without high-quality, knowledge-intensive jobs and the innovative enterprises that lead to discovery and new technology, our economy will suffer and our people will face a lower standard of living."[72] Zalmay Khalilzad, the former American ambassador to Afghanistan, has argued that "to remain the preponderant world power, U.S. economic strength must be enhanced ... by generating and using superior science and technology."[73] And Wendy H. Schacht, senior researcher for the Congressional Research Service, has noted that "over the long run, enhanced technologies and manufacturing techniques can be very important for increasing productivity and economic growth."[74] In this way, inadequate funding of research and development on energy technologies greatly contributes to the deteriorating competitiveness of the U.S. economy.

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[62] Robert M. Margolis and Daniel Kammen, "Underinvestment: The Energy Technology and R&D Policy Challenge," *Science* 285(5428), p. 690–692.

[63] Daniel M. Kammen and Gregory F. Nemet, "Reversing the Incredible Shrinking Energy R&D Budget," *Issues in Science & Technology* (Fall, 2005), p. 84.

[64] National Science Board, *Science and Engineering Indicators 2004* (Arlington, VA: National Science Foundation, 2004), p. A6-5.

[65] *The Economist*, "Trade, Exchange Rates and Budgets," 380(8485) (July 8, 2006), p. 93.

[66] Organization for Economic Cooperation and Development, *Science, Technology, and Industry Scoreboard: 2005*, available at http://www.oecd.org/dataoecd/18/21/35471711.pdf.

[67] Richard M. Jones, "Building Support in the House for the DOE Office of Science," April 12, 2005, available at http://www.aip.org/fyi/2005/054.html.

[68] Steve Roach, "More Jobs, Worse Work," *New York Times*, July 22, 2004, p. A21.

[69] Robert A. Blecker, "The Trade Deficit and U.S. Competitiveness," In: Candace Howes and Ajit Singh (Eds.) *Competitiveness Matters: Industry and Economic Performance in the United States* (Ann Arbor, MI: University of Michigan Press, 2000), p. 53–54.

[70] Norman Augustine, "Rising Above the Gathering Storm," *Statement Before the Committee on Science, U.S. House of Representatives*, October 20, 2006, p. 2.

[71] American Electronics Association, *Losing the Competitive Advantage? The Challenge for Science and Technology in the United States* (Washington, DC: AEA, 2005).

[72] National Academy of Sciences, *Rising Above the Storm: Energizing and Employing America for a Brighter Economic Future* (Washington, DC: National Academies Press, 2006), p. 3.

[73] Zalmay Khalilzad, "Losing the Moment? The United States and the World After the Cold War," *The Washington Quarterly* 18(2) (Spring, 1995), p. 84–102.

[74] Wendy H. Schacht, "Manufacturing, Technology, and Competitiveness," In: Wendy H. Schacht (Ed.) *Critical Technology* (New York: Penny Hill Press, 2000), p. 46.

Table 1
Comparing incremental vs. transformative R&D

| Incremental R&D | Transformational R&D |
|---|---|
| Emphasis on refining existing technology | Looks beyond existing technologies to tomorrow's needs and requirements |
| Operates within traditional programs and offices | Does not follow prescribed orthodoxy |
| Tends to alter processes and materials rather than systems | Tends to alter entire technological systems |
| Promotes incremental and cumulative change | Promotes radical and transformative change |

## 3. Proposing a solution: the creation of ARPA-E

Collectively, inconsistent energy policies, incremental progress on energy technologies, and inadequate support of energy institutions have made the country increasingly susceptible to recurring energy crises. Rising energy demand yet stagnating supply, growing volatility of energy markets, increasing dependence on foreign supplies of fuel, a degrading electric transmission and distribution grid, and continually mounting environmental costs of energy production and consumption—demand a robust and sustained research strategy on energy technologies. As Stephen Chu, Director of the Lawrence Berkeley National Laboratory, succinctly stated, ''The energy problem is *the single most important problem* that has to be solved by science and technology in the coming decades''[75]

One would think that the sheer magnitude of the energy problems facing society would spur quick, decisive action yielding profuse and ecumenical solutions. Instead, the problems with the current method of thinking merely recur. This is partly because, unlike the beginning of the Great Depression on October 29, 1929, the December 7, 1941 attack on Pearl Harbor, the Soviet launch of Sputnik on October 4, 1951, the explosion of the *Challenger* Space Shuttle on January 28, 1986, and the September 11, 2001 terrorist attacks on the World Trade Center and Pentagon, there is no ''crisis like moment'' to spur public sentiment and political action. Instead, we have what William A. Wulf, President of the National Academy of Engineering, calls a ''creeping crisis.''[76] Like each of the ''proverbial blind beggars'' feeling an individual part of an elephant, the public and many federal offices hear about nuclear security, energy security, alternative energy sources, national laboratories, and big computers, but are left with no sense of an urgent, coherent mission to quickly integrate or synergize American energy research.[77]

To respond to these challenges, a new type of organization called the Advanced Research Projects Agency-Energy (ARPA-E) should be created. ARPA-E would fundamentally differ from any other existing organization conducting energy research in four ways: (1) it would focus exclusively on transformational R&D; (2) it would be mission-oriented to focus on broad technology challenges rather than narrow technological programs, thus escaping the technical ''problem-solver'' mentality of most engineers; (3) it would make no distinction between basic and applied research, instead promoting technologies until they are completely diffused into the marketplace; and (4) it would operate according to an innovative institutional structure to avoid many of the problems plaguing DOE research practices.

### 3.1. An exclusive focus on transformational R&D

The essential difference between energy R&D with radical/creative and traditional/conventional properties concerns a distinction between incremental and transformative research. *Incremental* R&D focuses on refining existing technology, fits neatly into established programs and offices, and tends to produce change at the process and material level, rather than the systems level. In contrast, *transformational* R&D focuses on looking beyond today's needs and requirements, challenges conventional program structure, and produces change at the systems level (see Table 1).

Philosophically, the same institution can conduct both incremental and transformational research. Admittedly, the national laboratories occasionally produce transformational breakthroughs in technological systems. However, in a world of limited resources and rigid institutional frameworks the two are mutually exclusive. Most program managers tend to choose an incremental research strategy because it is much safer: it can more easily appease sponsors, it is less risky, it fits into convention, and it promotes the existing R&D system of which the researchers are a part of.

The difference between incremental and transformational R&D parallels a debate in the 1970s between soft and hard energy paths. In his widely synthetic work, Amory Lovins commented that the dominant energy strategy for the country was ''strength through exhaustion,'' or simply expanding supplies of energy to meet the extrapolated demands of a dynamic economy, treating those demands as homogeneous—as aggregated numbers representing total energy in a given year. Such a strategy, termed the *hard* path, utilized large, mammoth, centralized fossil-fuel and nuclear facilities to meet energy demand. The hard strategy was subscribed to by the federal government, energy companies, and energy think tanks such as

[75] Stephen Chu, ''Should Congress Establish ARPA-E?'' *Statement Before the Committee on Science, U.S. House of Representatives*, March 9, 2006, p. 3.

[76] William A. Wulf, ''Remarks on Rising Above the Gathering Storm,'' *Statement Before the Committee on Science, U.S. House of Representatives*, October 20, 2005, p. 3.

[77] Secretary of Energy Advisory Board, *Critical Choices: Science, Energy, and Security* (Final Report of the Task Force on the Future of Science Programs at the Department of Energy), October 13, 2003, p. 12.

the Edison Electric Institute and Electric Power Research Institute. [78]

Lovins argued that hard path suffered from a number of significant problems. Large generators cannot be mass produced. Their centralization requires costly distribution systems. They are inefficient, often not recycling excess thermal energy. They are much less reliable, unreliability being a graver fault that requires more and costlier reserve capacity. They take much longer to build, and are therefore exposed to escalated interest costs, mistimed demand forecasts, and wage pressure by unions. Ultimately, the hard energy path is woefully inefficient. To heat water to thousands of degrees to produce steam that turns a turbine, generates electricity, and transmits that electricity over a hundred miles only so that someone can boil water a few hundred degrees is ''like cutting butter with a chainsaw—which is inelegant, expensive, messy, and dangerous.''[79]

In contrast, Lovins proposed a *soft* path promoting energy technologies that were (a) diverse, providing energy in smaller quantities from decentralized sources; (b) renewable, operating on non-depleteable fuels; (c) simple, or relatively easy to understand; (d) modular, or matched in scale to energy needs; and (e) qualitative, or matched in energy quality to end-use needs. Basically, a decision about the pursuit of hard versus soft energy paths boils down to a set of two questions: Do we want a small to medium scale, decentralized energy system that is more efficient, subject to local control by the same people who want the energy, operates with minimal disruption of ecological services, remains resilient to disruptions and terrorist assaults, is equally available to all future generations, highly beneficial to developing countries and truly renewable? Or do we want a plutonium or fossil fuel economy, centrally administered by a technical elite, sure to promote international proliferation and increase inequity and vulnerability, which increases the dependence of poor countries on rich countries, requires garrison-like security measures at many points in the fuel cycle, wastefully generates and distributes energy at too high a quality, must be uselessly degraded to fit the majority of end uses, and remains based on highly uncertain projections about fuel availability and capacity factors?

The point is that the true contest between hard and soft energy paths had little to do with the technologies themselves. It had much more to do with the way that energy policymakers *thought* about energy. In a theoretical sense, the soft and hard paths are both possible, and can be pursued simultaneously. One could conceivably integrate a soft energy technology—a collection 1 kW solar panels, for instance—with a hard energy technology—on the cooling tower of a 1000 MW nuclear facility. Yet while hard and soft paths may not be theoretically exclusive, they are still ''culturally and institutionally antagonistic.''[80] The tools required for each inhibit the availability of the other. ''Soft and hard paths are culturally incompatible,'' Lovins concluded, since ''each path entails a certain evolution of social values and perceptions that makes the other kind of world harder to imagine.''[81]

Moreover, the choice between hard and soft paths also requires completely different orders of thinking. Two distinctions must be made—one between deciding whether to live off of natural capital or income; another between tactics and strategy. A policy based on depleting fossil fuels and polluting the environment more than just ''different'' than one utilizing non-depleting and non-polluting ones. Obviously, it will always be seemingly cheaper and easier to live off natural capital than income—for as long as our natural capital lasts, the economics of living off soft resources differs from depleting fossil fuels as chess differs from checkers. The very rules of the game are different, though the board on which the two games are played looks the same.

One game recognizes permanence and ecological discipline as rules restricting legitimate moves. The other game has no such rules. A good move in the checkers of hard-path geocapital consumption economics is not usually a good move in the soft-path chess of permanent renewable income economics. In checkers, all pieces are comparable; in chess, essential and qualitative differences exist. A definite decision must be made the about direction we move—renewable or fossil—before we decide about the rate at which we move in that direction.[82] One strategy is based on depleting natural capital, the other income; both strategies have their own tactics, but those tactics make sense if *only* one game is being played—not both.

Much like the distinction between hard and soft energy paths, the choice between incremental and transformational research strategies is about more than just conducting research. It is about how institutions conceive of the entire research and development process. Trying to do both at once—at least in terms of incremental or transformational pathways—is like playing chess and checkers simultaneously on the same board. The intellectual, financial, and institutional resources required for each strategy limit the efficacy of the other. It remains unlikely that a single institution could effectively do both—especially when stove-pipes among various programs prevent cooperation and minimize accountability.

[78] See Amory Lovins, ''Energy Strategy—The Road Not Taken?'' *Foreign Affairs* 55 (1976–1977), p. 65–96; Amory Lovins, *Soft Energy Paths: Towards a Durable Peace* (New York: Harper Collins, 1979); and Amory Lovins, ''A Target Critics Can't Seem to Get in Their Sights,'' In: Hugh Nash (Ed.) *The Energy Controversy: Soft Path Questions and Answers* (San Francisco: Friends of the Earth, 1979), p. 15–34.

[79] Amory Lovins, ''A Target Critics Can't Seem to Get in Their Sights,'' In: Hugh Nash (Ed.) *The Energy Controversy: Soft Path Questions and Answers* (San Francisco: Friends of the Earth, 1979), p. 26.

[80] Hugh Nash, ''Foreword,'' In: Hugh Nash (Ed.) *The Energy Controversy: Soft Path Questions and Answers* (San Francisco: Friends of the Earth, 1979), p. 1–6.

[81] Amory Lovins, ''A Target Critics Can't Seem to Get in Their Sights,'' In: Hugh Nash (Ed.) *The Energy Controversy: Soft Path Questions and Answers* (San Francisco: Friends of the Earth, 1979), p. 30.

[82] For an excellent summary of this type of thinking, see Herman E. Daly, ''On Thinking About Future Energy Requirements,'' In: Charles T. Unseld, Denton E. Morrison, David L. Sills, and C.P. Wolf (Eds.) *Sociopolitical Effects of Energy Use and Policy* (Washington, DC: National Academy of Sciences, 1979), p. 232–240.

To emphasize this apparent conundrum, consider that DOE research on advanced lighting tends to focus on three separate elements of a lighting system—the light source, fixtures, and controls. Improvements to lighting technologies, when they are made, tend to revolve around augmenting the luminance, chromacity (color), and quality of light bulbs; refining automatic controls; producing better ballasts; and so on. Lighting devices are still mostly controlled by humans (who turn the light "on" and "off"), rarely incorporate natural light, and are wasteful in the sense that in many forms (such as overhead lights) they tend to illuminate the entire room or hallway rather than the immediate space around the user. When solar energy is incorporated into lighting systems, it must be captured, converted and stored.[83] Such ideas ignore more novel, adaptive, multi-functional approaches to adapting sunlight to a host of end-use applications in buildings. They disregard that sunlight has many possible uses in buildings including direct use as interior lighting and radiant heating of occupants, and that solar energy can be easily converted into hot water and electricity.

In contrast, a more transformational research strategy aimed at lighting could center on the creation of anticipatory lighting systems that integrate multi-functional solar technologies.[84] Such systems could use vision-based sensing and scene analysis of information so that the lights interact with room occupants, other luminaries, building energy systems, and external sources of information, such as the real-time price of electricity or sudden increases in sunlight. Anticipatory lighting systems would require distributed decision-making based on approximate reasoning and anticipatory algorithms and adapting the spatial distribution, intensity, and chromaticity of light emerging from luminaries based on a host of input parameters to continually optimize system performance from a lighting quality and energy-efficiency perspective. To oversimplify, the incremental strategy—still undertaken by the DOE—focuses on improving light bulbs. A transformational strategy focusing on improving the entire lighting system rarely occurs.

As a second example, current research on biomass and biofuel feed-stocks is split between the U.S. Department of Agriculture (USDA) and the DOE, with further divisions between basic science on genetics and genomics and the deployment of biofuel technologies. The overall mission of the DOE's bioenergy program is to develop biomass feedstock production and conversion technologies capable of providing significant fractions of domestic demands for transportation fuels, electric power, heat, chemicals, and materials. Such a research strategy remains centered on (a) the use of traditional feedstocks such as switch grass, rapeseed, and corn in (b) open-air climates located in (c) areas that have fertile and semi-fertile sources of soil. The overall mission of the USDA is to increase the use of agricultural crops and forest resources, improve crop tolerance and disease resistance, create jobs, and enhance income in America's rural sector. Improvements on biofuels within these two paradigms have tried to meet both goals, focusing on genetically engineering plants to use fewer pesticides, finding alternative feedstocks, and searching for suitable areas of land on which these plants can grow.

Yet these tenets discount more transformative techniques such as the use of photo-bioreactors for biofuel production, where biofuels can be produced using nontraditional feedstocks in closed-air climates in areas with little sources of fertile soil. Photo-bioreactors use solar energy to grow biomass in a self-contained network of pipes. Solar troughs—which use mirrors to concentrate sunlight—are placed on top of pipes filled with algae. In open-air environments, the sheer intensity of sunlight prevents algae from harnessing more than around 5% of solar energy due to photosynthetic saturation. The photo-bioreactor, however, uses the solar troughs to simultaneously generate electricity from the infrared light the algae never users and reduces the intensity of light distributed to the algae, so that 1 $m^2$ of sunlight can fuel up to 20 $m^2$ of algae. Since the photo-bioreactor is solar-powered, closed-loop, and uses very little water, it could be used to produce biofuels in deserts and other unsuitable or untraditional crop areas, and would ensure that such feedstocks are self-contained and would have little to no disruption on current food supply.[85]

Think about transportation as a final example. Research on transportation is spit between the DOE and the Department of Transportation (DOT). The entire DOE strategy can be divided into three sections: improving automobile performance (through better engines, light weight materials, and hybridization), promoting alternative fuels, and introducing hydrogen fuel cells into the market. The DOT is more concerned with vehicle infrastructure integration, advanced vehicle control, driver assistance, dynamic signal timing on arterials, and lessoning the extent and severity of traffic accidents. Both visions remain rooted to the same assumptions: using human-driven, self-powered, wheeled vehicles traveling on dedicated roadways and interstates. This dominate method of transportation brings with it a multitude of problems including an overdependence on foreign oil, vulnerability to economy-damaging energy price shocks, unsustainable air pollution, an aging and expensive transportation highway infrastructure that requires significant land use, and a growing traffic congestion problem that affects the safety and productivity of the motoring public.

Contrast such incremental thinking with dual mode transportation systems consisting of a network of automated personal land transit vessels with an associated electric guide-way infrastructure. The intent would be to transition from interstate, state, and local highways to integrated, automated guide-ways. In addition to being fully automated, vehicles could interact with other vehicles, buildings, and infrastructure,

[83] U.S. Department of Energy, Office of Science, "Basic Research for Solar Energy Utilization," Notice DE-FG02-06ER06-15, April 19, 2006, available at http://www.science.doe.gov/grants/FAPN06-15.html.

[84] See Jeff Muhs, "Identifying and Understanding Innovation Gaps in America's Energy R&D Portfolio," Oak Ridge National Laboratory (Unpublished Manuscript), 2006.

[85] Ibid.

Table 2
Examples of incremental vs. transformational R&D strategies

| Known problem/need | Energy relevance | Incremental R&D strategy | Transformational R&D strategy |
|---|---|---|---|
| Need lights that consume less energy | Lighting consumes roughly 20% of all electricity generated in the U.S. | Design static electric lighting systems—such as compact fluorescent light bulbs and solid state lighting systems—designed for "worst-case" scenario needs | Anticipatory lighting systems that adapt spatially, temporally, and chromatically to maximize quality and efficiency |
| Need technologies that more effectively utilize solar energy | Solar energy provides around 0.2% of electricity in the U.S. meaning its relative abundance remains largely untapped | Improve the efficiency of thin-film photovoltaic cells | Multi-functional and end-use responsive solar systems using direct sunlight and energy conversion |
| Need new sources of fuel for bioenergy facilities | Alternative fuels help reduce U.S. dependence on foreign supplies of petroleum | Improve the energy density of bio-crops through genetic engineering | Photo-bioreactors that can efficiently produce bio-fuels anywhere from algae grown in pipes |
| Need automobiles with better fuel economy and less air pollution | Current mode of land transportation plays a significant role in oil dependence, air pollution, and congestion | Increase fuel economy standards and improve light-weight vehicle materials and vehicle hybridization | Dual-mode transportation system utilizing automated, electric guide-ways |

and could platoon or couple together for maximum efficiency. If made to run predominately on electricity, such a system could be much safer, cleaner, and more efficient than the way we conceive of transportation currently.

In each case, potentially novel and creative energy R&D is discarded in favor of incremental, conventional research (see Table 2). It is clear that existing energy research institutions have difficulty doing both incremental and transformational research at once.

### 3.2. A mission-oriented focus on broad technology challenges

Instead of focusing on particular technologies or programs, ARPA-E should organize its R&D around technology *challenges*. The organization would need to be completely mission driven, much like the Defense Advanced Research Projects Agency (DARPA). DARPA was created in 1958 after the Russian launch of Sputnik provoked a U.S. military investigation that revealed bureaucratic infighting and an unwillingness to take risks within the National Aeronautics and Space Administration and parts of the Department of Defense. President Dwight Eisenhower ordered the creation of DARPA as a way to avoid the disconnected manner that space and defense programs typically undertook their R&D.

Rather than wed researchers and managers to specific technologies, DARPA is instead focused on achieving a single mission: to sponsor revolutionary, high-risk research that bridges the gap between scientific discovery and military use. Since its inception, DARPA has helped develop better command and control systems for nuclear missiles, improved semiconductor manufacturing techniques, laid the groundwork for the internet by devising massive parallel computer processing, built two radar evading "Stealth" aircraft (the F-117 and the B-2), and invented phased array radars, night-vision goggles, and key parts of unmanned aerial vehicles global positioning satellites.[86]

F. L. Fernandez, Director of DARPA from 1998 to 2001, commented that within all large institutions like the DOE, "organizational stove pipes develop and these stove pipes often have risk-averse, parochial views which can misjudge the potential for new, technologically enabled opportunities and threats, especially if the technology is high risk."[87] To foster creativity and enable managers to undertake risky energy projects, ARPA-E should operate similarly by ensuring that every project matches its fundamental mission of promoting transformational energy R&D.

### 3.3. A more nuanced view of the science and technology R&D process

To minimize stove-piping, ARPA-E should promote all stages of research and development on energy technologies—from invention and design to commercial diffusion and marketing. Such a research model should avoid demarcating between research stages. Instead, it should fully develop energy technologies to match pressing energy challenges.

To respond to similar challenges regarding technological diffusion, In-Q-Tel was been created by the U.S. intelligence community to help bring radical R&D projects to the marketplace. In-Q-Tel was created for the U.S. Central Intelligence Agency (CIA) to respond to a perceived "intelligence deficit" in advanced technologies caused by a perceived movement of capital and talent to the commercial sector during the internet boom of the late 1990s. The CIA believed that the American intelligence community had somehow become disconnected to the creative forces that underpinned the digital economy and, of equal importance, that many in Silicon Valley and emerging technological firms knew or cared little about the CIA's needs.

[86] Defense Advanced Research Projects Agency, *DARPA: Bridging the Gap, Powered by Ideas* (Washington, DC: DARPA, February, 2005), p. 1–28.

[87] F. L. Fernandez, "Hearing on ARPA-E," *Statement Before the House Committee on Science, U.S. House of Representatives*, March 9, 2006, p. 1.

Table 3
Differences between Methods of Research at the DOE and ARPA-E

| Current methods of R&D related to | U.S. Department of Energy | ARPA-E |
|---|---|---|
| Mission | To manage nuclear weapons; clean up environmental pollution; conduct research and development on energy and basic science | To design creative, risky, transformational energy technologies |
| Management structure | Hierarchical, with multiple vertical and horizontal layers between scientists and managers | Flat, with an emphasis on the program manager |
| Degree of risk | Low | High |
| Primary historical focus | On incremental improvements of existing technology | On radical changes to technological systems |
| Staff turnover | Indefinite | Fixed |

In response, In-Q-Tel was created as a strategic venture capital firm that operates as an independent, non-profit, government funded institution that receives oversight from the CIA. In-Q-Tel performs manifold functions: it engages start ups, emerging and established companies, universities, and research laboratories to identify technology innovations and products that can solve the American intelligence community's most pressing problems. In-Q-Tel employs venture capital investments, often coupled with product development funding, to create innovative intelligence technologies. Any profits it makes—$15 million so far from 2001 to 2006—get funneled back into helping the firm meet its mission.

In-Q-Tel commonly uses three approaches to support technologies: (1) giving seed money (grants up to $300,000) to accelerate university research on ideas that are not quite ready for commercial diffusion; (2) performing a ''matchmaking'' function that helps academics license their discoveries with a company already working with In-Q-Tel; and (3) financing money to start-up companies to develop and manufacture products.[88] As Catherine Cotell, Vice President of Strategy for In-Q-Tel, explained, ''In-Q-Tel fosters the development of strong companies which produce commercially viable technologies that at the same time solve critical intelligence community mission challenges.''[89]

To date, In-Q-Tel has supported more than 50 companies which in turn, have developed advanced data-mining software, nanotechnology devices, internet security programs, searching and indexing technologies for open-source documents, and improved wireless network security technologies. They are what the *Scientific American* named ''a high-powered, in-house technology incubator.''[90] They have proven so successful that, in 2002, the U.S. Army established its own $25 million independent venture capital firm to promote promising military technologies, and National Aeronautics and Space Administration started its own $10 million venture capital firm in 2006.

### 3.4. An innovative institutional structure

DARPA and In-Q-Tel possess a research culture almost the exact opposite of the traditional centralized, peer reviewed and layered research process undertaken by federal organizations such as DOE, USDA, and DOT. Instead of relying on mammoth programs with hundreds of staff, small groups of program managers exercise extensive power in directing high-risk technological projects.[91] To respond to the institutional problems of incrementalism, ARPA-E could operate with a flat management structure and a quick staff turnover. ARPA-E could compliment government research on energy, but would fundamentally differ in its staffing procedures, strategy, and structure. ARPA-E would recruit and maintain personnel differently. It would seek excited, fresh, and energized individuals who possess a sense of mission relating to energy research.

Like DARPA and In-Q-Tel, ARPA-E should be as lean and streamlined as possible. In-Q-Tel, for instance, employs a small number of staff—only 45 individuals working in two offices—and turns them over on a 3–5-year basis.[92] DARPA rotates their scientists and engineers out of the organization every 3–5 years. In contrast to a DOE research system heavily centered on the same individual programs, ARPA-E would need to be supportive of transparent and accountable programs that are clearly defined and have precise objectives, capable of cancelling projects quickly and recognizing failures, and focused entirely on breakthrough, new ideas (Table 3).

## 4. Conclusion

First, while transformational R&D does occasionally occur within the present energy system, it is a product of circumstance rather than design. Engineers and scientists remained predominately concerned with changing processes and components rather than systems. Research is stove-piped in at least

[88] David Malakoff, ''Technology Transfer: CIA Looks to Universities for Cutting-Edge Tools,'' *Science* 304 (April 2, 2004), p. 30.

[89] Catherine Cotell, ''The Need for ARPA-E?'' *Statement Before the Science Committee of the United States House of Representatives*, March 9, 2006, p. 1–4, 6.

[90] Daniel G. Dupont, ''The Company's Company: Venture Capitalism Becomes a New Mission for the Nation's Spymasters,'' *Scientific American* (August, 2001), p. 26.

[91] For more on these types of differences, see Stephen Chu, ''Should Congress Establish ARPA-E?'' *Statement Before the Committee on Science, U.S. House of Representatives*, March 9, 2006, p. 3–5; Melanie Kenderdine, ''Should Congress Establish ARPA-E?'' *Statement Before the Committee on Science, U.S. House of Representatives*, March 9, 2006, p. 1–6.

[92] Wendy Molzahn, ''The CIA's In-Q-Tel Model—Its Applicability,'' *Acquisition News Quarterly* (Winter, 2003), p. 47–61.

three ways: (a) because of rigid distinctions between science/technology and basic/applied research; (b) because most scientists and engineers are trained as problem solvers rather than problem definers; and (c) because channels of coordination between external organizations (such as the USDA and DOT) and within the DOE remain confusing and complicated. The national laboratories are sponsor driven rather than mission driven, R&D programs are poorly funded compared to other federal activities, and inconsistencies make it virtually impossible to sustain a coherent, long-term national energy policy.

Second, the diffuse and growing challenges facing the American energy sector demand a fundamental rethinking and radical redesign of the processes the country utilizes to produce energy technologies. Contemporary research methods are plagued by institutional self-interests, less interdisciplinary teaming, and perpetual incrementalism rather than radical innovation. With the way things stand, transformational research on multi-functional anticipatory lighting systems, photo-bioreactors for bio-diesel production in deserts, and a radical dual-mode land transportation system do not fit neatly into established federal departments, programs, or offices. The DOE and national laboratories were not designed to pursue transformational R&D projects, and program mangers and policymakers often lack the personal, organizational and political will bring them forward. Managers at the DOE national laboratories conform to rather than confront the conventional wisdom and paradigms of their federal sponsors because of programmatic and financial risks to their organization of nonconformity are too great. In turn, individual researchers seeking to keep themselves gainfully employed ‘‘follow the money’’ down predetermined R&D pathways rather than expending considerable time and energy challenging existing paradigms and process structures. The evidence suggests that America's risk tolerance for transformational energy R&D at the federal level is growing, but personal, programmatic, political, organizational, social, and socio-scientific attitudes and values threaten to disrupt systems-level innovation. Like the DOD's creation of DARPA and the intelligence community's establishment of In-Q-Tel, the DOE needs to create and fund an independent organization—ARPA-E—dedicated primarily towards conducting transformational energy R&D.

Third, the energy challenges facing the country will only grow more urgent with time—meaning that the sooner an ARPA-E like organization is created the better. If one accepts the idea that our current strategy of ‘‘strength through exhaustion’’ is simply depleting natural capital at a rate far faster than it can be replenished, then our society is squandering precious and increasingly finite natural resources to produce energy. Albert Einstein once said that the ‘‘significant problems we face today cannot be solved at the same level of thinking we were at when we created them.’’ As a culture, we can choose either to proactively undertake a transformative energy research strategy now, or wait until the inescapable laws of nature force us to.

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